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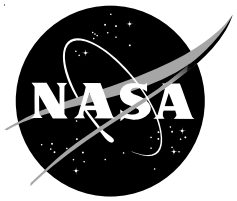

Wind and Mountain Wave Observations for the Pathfinder Hawaiian Flight Test Operation

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Under NASA Contract NAS 4-50066

January 1999

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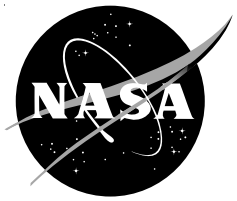

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WIND AND MOUNTAIN WAVE OBSERVATIONS FOR THE PATHFINDER HAWAIIAN FLIGHT TEST OPERATION

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1. INTRODUCTION

In support of NASA's Environmental Research Aircraft and Sensor Technology (ERAST) program, the Pathfinder solar electric powered Remotely Piloted Aircraft (RPA) conducted flight test operations at the Navy's Pacific Missile Range Facility (PMRF) at Barking Sands, Kaua'i, Hawaii, from May to November 1997 and from June to August 1998. This vehicle is designed to operate at low speeds and low Reynolds numbers for long duration flights at altitudes above 60,000 feet. During these flights the Pathfinder aircraft established three successive altitude world records for propeller driven aircraft. Notably Pathfinder achieved 67,400 feet on June 9, 1997; 71,350 feet on July 7, 1997 and 80,201 feet on August 6, 1998.

Since Pathfinder has a very low wing loading it is sensitive to atmospheric winds and wind gusts. Consequently, flight test operations with this vehicle require weather conditions with light surface winds (< 7 knots) for both takeoff and landing and high altitude winds less than the true airspeed (~ 40 knots at 40,000 feet, altitude). In addition, safe operations require little turbulence at all altitudes.

During the descent portion of the record altitude on June 9, 1997, the Pathfinder aircraft encountered a mountain wave updraft near 9,600 feet altitude approximately 3 nmi. west of the Kaua'i coastline. The objective of this paper is to describe the atmospheric conditions associated with the wave updraft. A brief overview of the airplane and climatological conditions relevant to Kaua'i, Hawaii is also presented. The use of trade names or names of manufactures in this document does not constitute an official endorsement of such products or manufactures, either expressed or implied, by the National Aeronautics and Space Administration (NASA).

2. THE AIRCRAFT

The 1997 Pathfinder aircraft was a flying wing configuration with a span of 99 ft and an 8 foot chord (Fig. 1). With a nominal gross weight of 500 lbs the wing loading was less than 0.64 psf. The aircraft was propelled by 6 electric motors powered by a solar-cell array on the upper surface during the day and by batteries at night. The aircraft has an equivalent airspeed of 17 knots with an overall climb and descent rate of nominally 220 ft /min. Pathfinder was designed to carry up to 50 lbs. payload to high altitude for atmospheric and ecosystem studies and sensor development.

This extremely light wing loading results in increased gust response and significantly increased sensitivity to winds during take off and landing as well as pre- and post-flight ground handling. High wind speeds aloft which exceed the Pathfinder true airspeed would make it difficult to navigate to the desired (and approved) airspace areas.

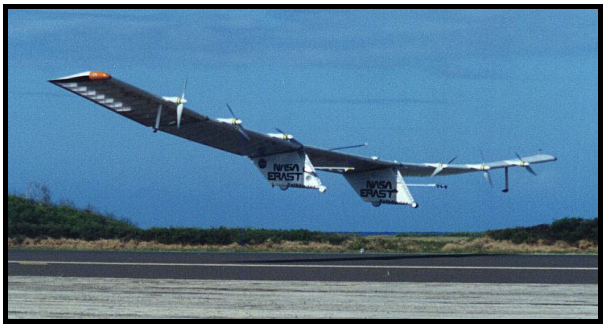

Figure 1. The Pathfinder Solar-powered Aircraft taking off June 9, 1997.

3. CLIMATOLOGY AND SITE WEATHER

PMRF is situated on the west side of the island of Kaua'i where the 5200 feet Mt. Waialeale and a north-south mountain ridge line divide the island in half just 16 miles to the east. These features block and divert the easterly trade winds allowing the west-side of the island to rest in a wind and rain shadow. For example, Lihue on the east or windward side of the island receives about 43 inches of rain per year while PMRF only receives about half that rainfall.

The PMRF climatology provides favorable operating weather conditions for RPA, particularly during summer. Seasonal wind speed differences between the Lihue and PMRF are highly dependent on direction. For example,

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during the December-February time period Lihue is sheltered from the dominant northwest winds by the mountains. Similarly, the mountains shelter PMRF during the summer months from the strong trades, which prevail at Lihue. At Lihue the annual winds average 10.8 knots while at PMRF the winds, predominantly gentle sea and land breeze winds, average 6 knots. During the summer and fall, wind speeds at the maximum wind altitude are within the allowable speed range for the Pathfinder airplane on approximately half of the days (Underwood 1996).

Surface and upper-air weather data for Pathfinder operations were acquired from the resident U. S. Navy weather station at PMRF. Lower altitude wind and turbulence profiles were monitored by Aerovironment, Inc. personnel using Doppler SOnic Detection And Ranging (SODAR) systems. During flight, NASA and Aerovironment, Inc. personnel continuously monitored weather conditions and forecasts to update the flight planners and mission managers on the weather conditions (Teets 1998).

4. THE FLIGHT DAY

Early on June 9, 1997 weather conditions were considered acceptable for a Pathfinder flight and winds at altitude were well under the maximum wind limit. Surface winds at PMRF were light and variable at 0600 Hawaiian Standard Time (HST), perfect for aircraft roll out. All upper level winds were less than true air speed limits as measured by the PMRF 0205 HST and 0438 HST rawinsonde balloons. National Weather Service (NWS) forecasts for upper level winds predicted a slight decrease over the next 24 hours, however during the same time period surface "trade" winds at Lihue were expected to increase slightly. Surface winds at PMRF were expected to increase to 10 knots by noon and then slowly decrease to light and variable at 1900 HST.

The balloons launched from PMRF and Lihue for flight 97-1 are listed chronologically in Table 1. A total of eleven rawinsonde balloons were released during the case study period. Figure 2 shows the PMRF rawinsonde measured temperatures from three balloons on June 9 and the one for June 10.

Table 1. PMRF and Lihue rawinsonde balloon release times and dates (all times, Hawaiian Standard Time).

PMRF Balloons	Lihue Balloons	Significant Events
Time	Time	Time
	0200 June 9, 1997	
0205 June 9, 1997		
0438 June 9, 1997		
0706 June 9, 1997		
		0845 Takeoff
1005 June 9, 1997		
1304 June 9, 1997		
	1400 June 9, 1997	
1657 June 9, 1997		
		1530 Peak Altitude
1914 June 9, 1997		
		2115 Wave encounter
		2300 Landing
	0200 June 10, 1997	
0532 June 10, 1997		

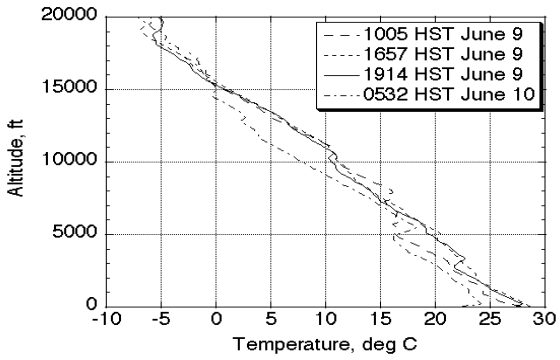

Figure 2. PMRF June 9 and 10 temperature profiles.

5. WAVE ENCOUNTER RESULTS

When air is forced over a mountain under statically stable conditions, individual air parcels are displaced from their equilibrium levels and undergo buoyancy oscillations as they move downstream of the mountain. In this manner an atmospheric wave is excited in the lee of the mountain. Meteorological conditions generally required for significant transverse wave formation include (1) wind speeds of 10-15 knots or more at ridge level and increasing in altitude, (2) winds aligned parallel to each other with height, (3) winds perpendicular to the ridge line (no more the 30 degrees off axis), and (4) a layer of enhanced stability in the temperature profile near the ridge altitude (Hopkins 1977).

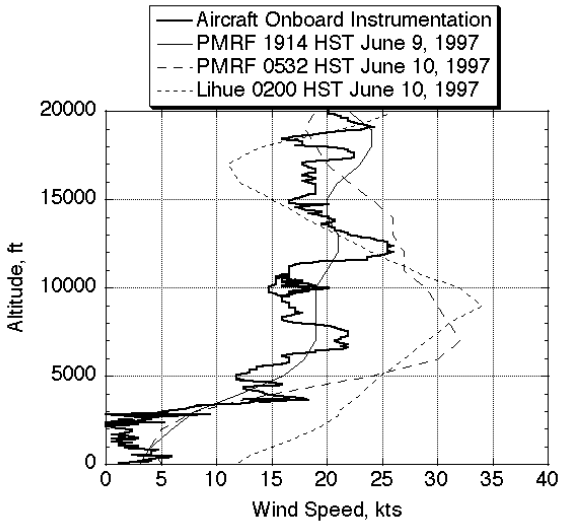

Figure 3. Upper air winds for June 9 and 10 from PMRF, Lihue, and aircraft instrumentation.

The June 9, 1997 wave updraft was encountered by the Pathfinder at 2115 HST. The conditions near encounter time indicated a very stable temperature profile (Fig. 2), winds at 5000 feet or ridge top near 15 knots (Fig. 3), and wind direction perpendicular to the ridge line. These winds were provided from three

sources: Pathfinder's onboard instrumentation (true airspeed indicator and Global Positioning System (GPS)), Lihue's NWS balloon released at 0200 HST June 10, and balloons from PMRF released at 1914 HST June 9 and 0538 HST June 10 (Fig. 3). Wind profile pair (PMRF 1914 HST and onboard instrumentation) closest to the encounter shows fair agreement with each other as did the post encounter wind profile pair (Lihue and PMRF). The later pair also shows that the winds strengthened between 5,000 and 12,000 feet after the 1914 HST PMRF balloon.

Aircraft GPS and ground based RADAR tracking data were used to reconstruct aircraft location and vertical motions observed during the wave encounter. The aircraft encountered the wave near 9,600 feet and over the next 15 minutes slowly lifted the aircraft 900 feet at 60 ft/min rise rate as shown in Figure 4. Figure 5 shows the reconstructed aircraft position and balloon drift trajectories (Bauer 1997) relative to the PMRF airfield during the wave encounter. Figure 6 shows balloon rise rates as a function of scalar down wind drift distance. Each of the balloon traces show a local rise rate maximum located near the 2 nautical mile wind drift distance. These maxima are associated with rise rate peak to peak variations of 90 to 170 ft/min. Although weak, the variations are taken to be a subtle indication of the updraft encountered by the airplane. The altitude of these balloon updraft peaks at 2 nmi drift distance was 10,500 to 11,000 feet for the 1657 and 1914 HST balloons and near 9,000 feet for the post-flight balloon at 0532 HST the next day. Based on the

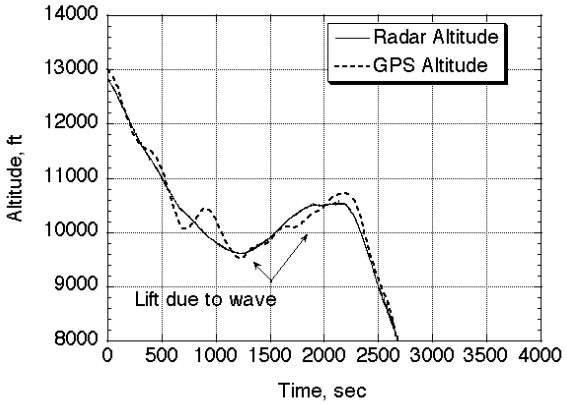

Figure 4. Pathfinder altitude time histories.

balloon trajectories and assuming that transverse wave crest axes extended perpendicular to the direction of balloon heading, the wave updraft region encountered by the airplane may have shifted to the 2.5 to 3.0 nmi off shore location after the 1657 and 1914 HST balloon observations. The stronger rise rate variation beyond 4 nmi. drift distance on the 0532 HST balloon was experienced between 14,000 and 20,000 feet. At the time of both Lihue (0200 HST) and PMRF (0532 HST) balloon observations, the wind speeds below 10,000 feet had increased markedly (Fig. 3).

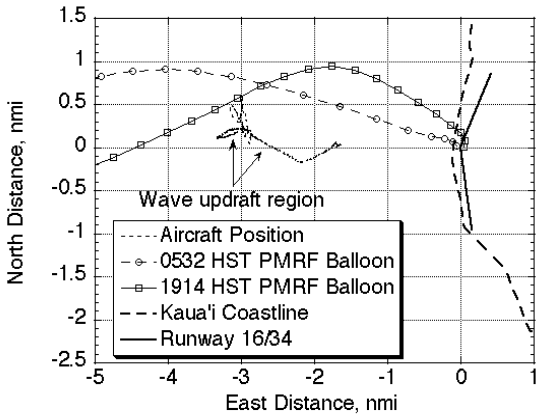

Figure 5. Pathfinder location during wave encounter with pre and post encounter balloon trajectories.

While in the wave updraft, the aircraft maintained a 60 ft/min climb rate. After exiting the wave the Pathfinder experienced a 300 ft/min descent rate which most likely include the effect of down draft air motion. This overall airplane climb rate variation is 360 ft/min, twice as great as indicated by the balloons at the 2 nmi drift distance location but considerably less than experienced by the last balloon above 14,000 feet altitude and beyond the 4 nmi drift distance. These observations indicate that the Pathfinder aircraft climb and descent performance is a sensitive observation tool for the study of weak or light wave activity. And conversely, the sensitivity of Pathfinder to weak wave motion indicates the value of closely monitoring the meteorological profile for conditions favoring wave development and the importance of extracting balloon rise rate data from the rawinsonde measurements. On subsequent Pathfinder flights balloon rise rates were monitored and analyzed for the presence of up- or down draft regions. Advising flight planners and mission managers of the possibility of wave encounter allows them to account for anomalous climb and descent rate behavior. In addition,

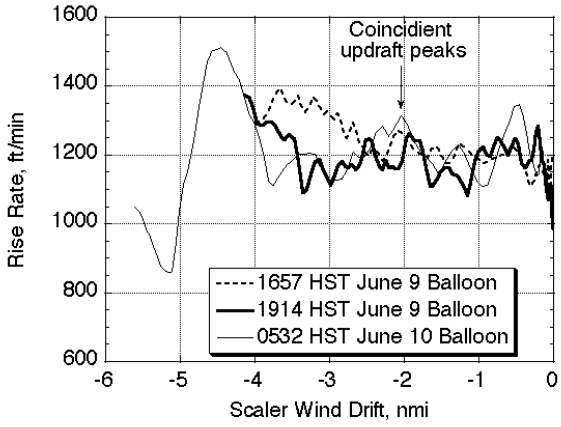

Figure 6. PMRF balloon scalar wind drift verses rise rate.

they were better prepared to navigate successfully through such phenomena and to allow additional flight time that may be needed prior to landing.

6. CONCLUSION

The solar power Pathfinder aircraft encountered a mountain lee wave on June 9, 1997 off the western coast of Kaua'i, Hawaii. The wave was encountered on the descent from 67,400 feet altitude in easterly flow at 9,600 feet. The wave updraft was clearly observed by the aircraft even though meteorological balloon data did not show large rise rate oscillations to strongly indicate the presence of a wave. The low airspeed and low wing loading make the Pathfinder airplane a sensitive tool for the observation and study of relatively subtle wave motion in the atmosphere. Analysis of balloon rise rates were helpful to flight planners and mission managers on subsequent flights.

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13. ABSTRACT (Maximum 200 words)

Light-wing-loaded aircraft such as the high altitude solar electric powered aircraft Pathfinder (designed by AeroVironment, Inc., Simi Valley, Ca.) are extremely sensitive to the wind speeds, wind shears, and turbulence and thereby are easily affected by mountain gravity wave activity. After reaching an altitude over 67,400 ft on June 9, 1997 the Pathfinder aircraft encountered a mountain wave during descent produced by the 5,000+ feet mountain of Hawaii's northernmost island of Kauai. This paper will discuss the atmospheric conditions and aircraft configuration for this case of mountain wave observed at the U. S. Navy's Pacific Missile Range Facility (PMRF) at Barking Sands, Kauai, Hawaii. This paper also describes the pathfinder airplane, climatology, and atmospheric conditions leading to the wave formation.

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